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Impact of short-term storage on frequency response under increasing wind penetration

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HIGHLIGHTS

- Assessing impact of short-term fast responding storage on system frequency response.
- Battery storage integrated into single-area AGC model of IEEE 24 bus RTS system.
- Improves CPS1 scores, procures lesser regulation and reduces generation cycling.
- Incentivizing short-term storage's regulation performance improves its economics.

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ABSTRACT

In this paper, the effort is to study the impact of short-term storage technology in stabilizing the frequency response under increasing wind penetration. The frequency response is studied using Automatic Generation Control (AGC) module, and is quantified in terms of Control Performance Standards (CPS). The single area IEEE Reliability Test System (RTS) was chosen, and battery storage was integrated within the AGC. The battery proved to reduce the frequency deviations and provide good CPS scores with higher penetrations of wind. The results also discuss the ability of the short term storage to benefit the system by reducing the hourly regulation deployment and the cycling undergone by conventional units, by dint of their fast response; and sheds light on the economic implications of their benefits.

1. Introduction

One of the significant impacts of renewable integration into the traditional and inflexible power system is upon the frequency response of the system [1]. Since these renewables, especially wind, are variable and unpredictable, the system is facing frequent and large ramps [2]. It has led to a significant rise in regulation reserves (to compensate the minute-to-minute mismatch between generation and load) and contingency reserves (10-min spinning and non-spinning).

The reserves from conventional generation units to tackle this issue related to renewable integration are proving to be insufficient [3]. Infact, using the slow moving conventional units for reserves proves counterproductive as at times they add to the net ACE and therefore the impose higher regulation requirements [4]. In addition to that whatever ramps they provide causes further fatigue and reduction of life cycle due to the heavy cycling [5] they are subjected to, which eventually contributes to increase in contingency reserves, operational & maintenance costs and overall production costs [6]. Overall, the need is not only for higher ramping capability requirements, but also for higher quality reserves, i.e., fast response (almost instantaneous) and precise control in providing regulation.

Fast ramp providers such as gas turbines, demand side resources and storage are touted as some of the technologies capable of supplying the required amount of regulation at the precisely scheduled moment [7]. Among these, the researchers, system planners and investors are specifically looking into storage to help out this new grid scenario [8,9]. Such technologies are capable of quickly responding to system regulation needs and increase the reliability of the system both in terms of decreasing outage quantities and cycling, and improving the frequency response by complying with NERC CPS [10].

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Nomenclature

$ACE_{1\text{-min}}$	1-min averages of the ACE over a year
B	frequency bias in terms of MW per 0.1 Hz
Δf	frequency deviations
$\Delta f_{1\text{-min}}$	1-min averages of the frequency deviations over a year
H	inertia
K_0	battery converter gain constant
L_{RT}	real-time load
Reg(t)	regulation requirement at hour t
T_A	actual tie-line flow
T_S	scheduled tie-line flow
T_d	battery converter time constant
V_{conv}	voltage across the battery converter
W_{RT}	real-time wind
ϵ	maximum acceptable steady-state frequency deviation
$\delta_{CPS}(t)$	additional regulation allocations at hour t to improve CPS standards

Abbreviation definitions

ACE	area control error
AGC	automatic generation control
ALFC	automatic load frequency control
AVR	automatic voltage regulator
CAES	compressed air energy storage
CPS	control performance standards
C–S	capacity–service ratio
DA	day-ahead
ED	economic dispatch
ISO	independent system operator
MCP	market clearing price
NERC	North American Electric Reliability Corporation
NL	net load
PHS	pumped hydro storage
RTED	real-time economic dispatch
RTS	reliability test system
SCED	security constrained economic dispatch
SCUC	security constrained unit commitment
SMES	superconducting magnetic energy storage
SoC	state of charge
UC	unit commitment

Storage technologies range from long-term (in terms of energy capability) bulk storage such as PHS and CAES to fast-responsive short term storage such as batteries, flywheel, SMES and super capacitors. Storage technologies though have been around for many decades, due to the high capital investments there are some impediments in their wide-spread usage in the grid. At this juncture, it is important to perform studies that evaluate their wide range of benefits and monetize them in order to increase their value for providing grid services [11].

In this paper, the effort is to study the impact of short-term storage technology in stabilizing the frequency response under increasing wind penetration. The frequency response is studied using AGC module, and is quantified in terms of CPS measures. The single area IEEE RTS system was chosen, which includes seven coal generators, two oil generators, three natural gas generators that participate in AGC. To this portfolio, fast responding battery storage module is added, and the improvement in frequency response and the various other benefits that storage brings are studied.

The organization of this paper is as follows. Section 1 gives an introduction of AGC and CPS measure. Section 2 presents the single-area AGC model and the storage model that will be integrated within AGC, and also discusses the manner in which the study accounts for the impact of increasing wind penetration on AGC. Section 3 discusses the results of simulation case studies for IEEE 24 bus RTS system. Finally, Section 4 presents the conclusions.

2. Automatic generation control and frequency performance

2.1. Automatic generation control

In the power system the load and generation are constantly changing and hence there is a need to balance out these fluctuations. When the load and generation are balanced the power system is said to be in equilibrium. The reactive power balance is carried out by the AVR that maintains the terminal voltage of each generator in the system to a constant value using its excitation system. The real power balance is achieved using two levels of control. The primary control loop is called the Automatic Load Frequency Control (ALFC) or the speed governor that adjusts the turbine output to match the change in the load. All the generators in the system contribute to change in generation to balance the load change. Apart from the power change, the load fluctuation causes a steady state frequency deviation which is balanced using the integral controller. This is called the secondary or supplementary control loop. Both the ALFC and the integral controller loop are together called as the Automatic Generation Control (AGC).

The AGC is like a remote control to the generator as it replaces some of the manual controls to change its generation level based on the input signal received at the system control center, i.e., raise, lower or no pulse indicating increase, decrease or maintain the current generation levels respectively. If frequency deviation is positive, the area generation has to be decreased and vice-versa. The main objectives of the AGC are:

i) Maintain the steady frequency
ii) Maintain the scheduled tie-line flows
iii) To distribute the required change in generation among the online generators economically

In a multi-area system, the AGC therefore corrects the frequency deviations and the tie-line deviations in a way that each control area compensates for its own load change. All the generators within a single area are typically replaced by an equivalent generator for that area ALFC. The measurement of the steady-state frequency deviation and the net tie-line deviation (actual-scheduled) is combined into a signal called Area Control Error (ACE). Using the ACE signal, the AGC for each area corrects its own load deviations.

$$\mathrm{ACE} = -10B\Delta f + (T_A - T_S) \tag{1}$$

where B is frequency bias in terms of MW per 0.1 Hz, usually a function of natural frequency response of the area. In the single area system the AGC has the function of regulating the system frequency in an economic fashion using the available generators. In this case, the ACE signal comprises of only steady-state frequency deviations. The dynamics of a system with different types of generations such as thermal, hydro, gas, oil, etc. depends on the contributions from various generations towards offsetting the ACE.

2.2. AGC in system operations

Fig. 1 shows the overall operational scheme of power system market within which AGC fits in the real-time operational environment [12]. Typically a day-ahead (DA) 24-h forecasts of load, wind together with generating unit offers are used by independent system operators (ISOs) to execute security constrained unit commitment (SCUC) and economic dispatch (SCED) respectively to make unit commitment decisions for the next day 24 h. The SCED also provides DA-MCPs for energy and ancillary services (i.e., regulation, spinning and non-spinning reserves). Then real-time economic dispatch (RTED) market is run at 5-min intervals considering the real-time load and wind data, and accordingly dispatches are adjusted based on the generation offers to meet the variability and uncertainties. The real-time MCPs for energy and ancillary services are obtained from RTED. In each ISOs, there are intermediate unit-commitment routines executed on the operating day for reliability purposes. Each generator based on its regulation offers is allocated regulation service in the real time market every 5-min (300 s). Based on the real-time market dispatch set points, AGC module gets appropriate signals to ensure that appropriate generators participate in AGC in each period to maintain reasonable frequency response against fluctuating net-load (difference between load and wind). Fast responding units such as storage find greater role and benefits by participating in such real-time markets due to their ability to move rapidly to the desired energy deliverance or absorption levels to mitigate the power fluctuations. Finally the control performance standards can be computed based on the frequency response obtained from the AGC module.

2.3. Frequency response – control performance standards

CPS1: It is a short term measure of the ACE i.e., the error between the load and the generation. It is an index to gauge the performance of the ACE in conjunction with the frequency error, and is computed as per (2). This control parameter reflects the extent to which the generators in the area are contributing towards correcting or hindering system frequency error correction.

$$\mathrm{CPS1} = (2 - \mathrm{CF})^{*}100\% \tag{2}$$

$$\mathrm{CF(Compliance\ Factor)} = \frac{\mathrm{ACE}_{1-\min}\Delta f_{1-\min}}{-10B\varepsilon^2} \tag{3}$$

where, ε, the maximum acceptable steady-state frequency deviation, is constant for a system. Presently, based on historical frequency deviations, ε is 0.018 for eastern interconnection, 0.0228 for western interconnection and 0.030 for ERCOT [13]. A CPS1 score of 200% implies that the actual measured frequency and the scheduled frequency are equal. It is recorded every minute but reported and evaluated annually. NERC has set the minimum long-term score to be 100% for a 12-month rolling average [10].

CPS2: It is the 10-min average value of the ACE signal. This is a monthly performance standard and limits the 10-min average of the ACE signal for each control area. The primary objective of CPS2 is to limit unscheduled power exchanges between balancing areas, and appropriately penalize if one area is found to over- or under-generate to get a very good CPS1 score, while impacting the neighbor area with excessive flows. CPS2 score is generally kept above 90%. However, since in this paper single area AGC simulation is investigated, CPS2 is not considered.

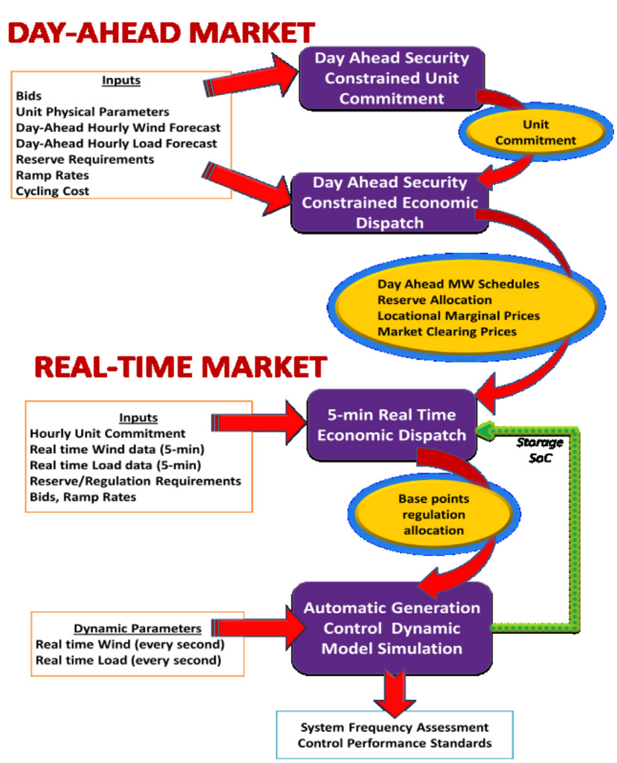

Fig. 1. AGC module in the overall system planning and operation.

3. Single-area AGC model with storage

3.1. Single-area system

The study was conducted using the modified IEEE 24 bus RTS system. This system has 2 oil generators, 3 natural gas generators and 7 coal (thermal) generators. These three classes of generators participate in the AGC, as shown in Fig. 2. Generally in AGC simulations, a group of generating units of same class (e.g., gas generators) is represented using one representative model. However in this study each generator is individually represented, in order to capture:

1. *Connection with SCUC and SCED*: Each generator's participation is dictated by the ED output, which decides regulation service allocations based on generator offers and physical constraints, and system conditions.
2. *Ramp rates*: Each generating unit, even within one class, has different per second ramping capability to AGC signals depending upon its capacity.

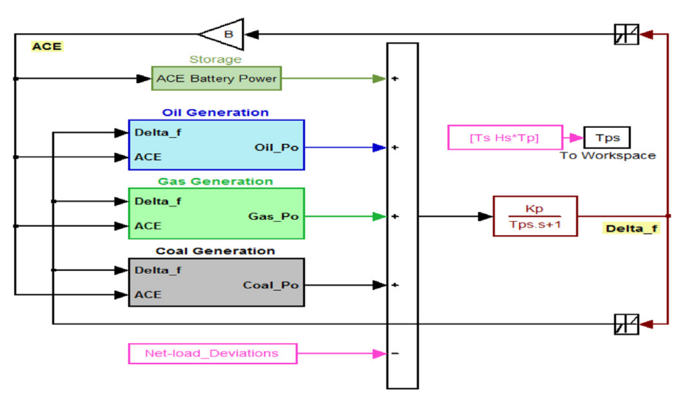

Fig. 2. Single area AGC simulation blocks – MATLAB Simulink.

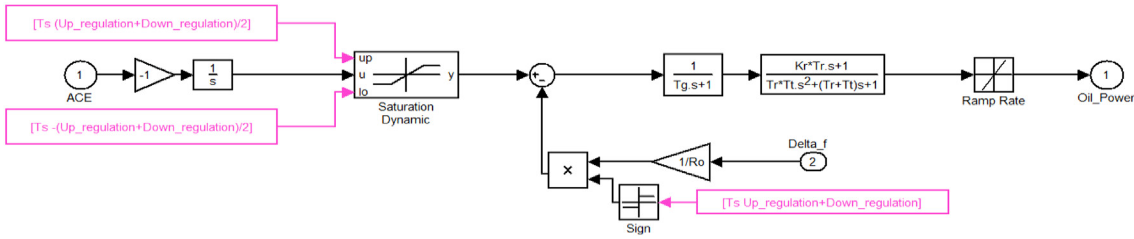

Fig. 3. Thermal unit AGC functionality – seven such models for coal units and two for oil units within Fig. 2.

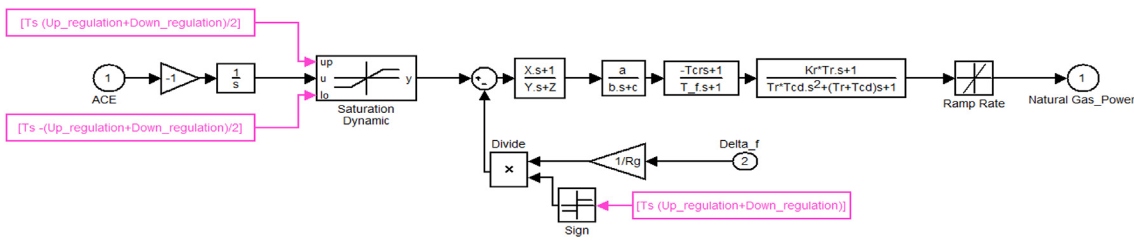

Fig. 4. Natural gas unit AGC functionality – three such models for natural gas units within Fig. 2.

The individual coal and oil generators are represented by thermal unit's governor, turbine and re-heater modules as shown in Fig. 3 with different ramp rates (3% per minute and 5% per minute of its rating respectively). The turbine is the prime mover for the generator that generates power and feeds it into the power system. The speed governor controls the steam input into the turbine. Natural gas unit is modeled using a gas turbine module with a reheater (with a ramp rate of 10% per minute of its rating) is represented as shown in Fig. 4 [14]. Rowen developed this mathematical model for the gas turbine [15]. This model consists of the single shaft gas turbine, its control system and its fuel system. The fuel system consists of two time constants. One time constant is associated with the gas valve positioning system and the second time constant is of volumetric type associated with the downstream piping and the fuel gas distribution manifold. The error between the reference and rotor speeds is fed into the speed governor. The model parameters are given in Table 1. Each generator's governor responds to the frequency deviation based on its respective droop characteristics defined by *R*.

Table 1
AGC model parameters.

Description	Parameter	Value
Speed governor lead time constant (s)	X	0.6
Speed governor lag time constant (s)	Y	1
Governor mode	Z	1
Valve positioner constant	a	1
Valve positioner constant	b	0.05
Valve positioner constant	c	1
Fuel time constant (s)	T_f	0.23
Combustion reaction time delay (s)	T_{cr}	0.3
Compressor discharge volume time constant (s)	T_{cd}	0.2
Speed governor regulation parameter (Hz/pu MW)	R_G, R_T	2.4
Power system gain constant (Hz/pu MW)	K_p	20
Power system time constant (s)	T_p	2
Frequency bias constant (puMW Hz^{-1})	B	0.425
Speed governor time constant (s)	T_g	0.08
Turbine time constant (s)	T_t	0.3
Re-heater time constant (s)	T_r	10
Coefficient of re-heat steam turbine	K_r	0.5
Gen integral controller gain (Hz/pu MW)	K_{IG}, K_{IT}	0.2

Each of these units' participation in frequency response is dictated by the economic dispatch that decides regulation service allocations, as discussed in Section 2.2. This feature is implemented using the dynamic saturation blocks in Figs. 3 and 4, which ensures the unit participates in AGC according to ED decisions. A particular unit may have governor response scheme, but it may not participate in it if the ED doesn't allocate a unit to provide regulation service, and this is accounted within the simulation by multiplying the droop parameter of respective unit with sign block of its regulation commitment during each period. The RTED module is not simulated after every 300 s of AGC simulation as shown in Fig. 1, in order to circumvent the computational requirements. Instead, the hourly unit commitments and the regulation allocations obtained from hourly DA-SCUC and SCED are used, and the unit participations in AGC are updated every hour (3600 s).

The net-load deviations computed every second is input as the disturbance to the AGC model as shown in Fig. 2. Since typically the generation base points are decided by 5-min RTED based on the average net-load in that period, the deviations are computed as shown in (4). The dead bands in Fig. 2 ensure that generators do not respond for frequency deviations within a band of ± 0.005 Hz.

$$\Delta \mathrm{NL}(t) = (L_{\mathrm{RT}}(t) - W_{\mathrm{RT}}(t)) - \mathrm{avg}_{5-\mathrm{min}}(L_{\mathrm{RT}}(t) - W_{\mathrm{RT}}(t)) \quad (4)$$

3.2. Inclusion of storage in AGC-battery

Typically storage technologies such as battery, flywheel and SMES [16,17] that have short-term energy capacity and respond faster are utilized to compensate the ACE instantaneously, and offset the frequency deviation. The operational logic behind short-

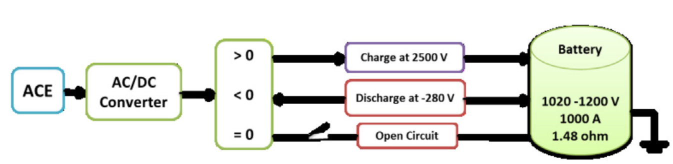

Fig. 5. Battery operation logic within AGC.

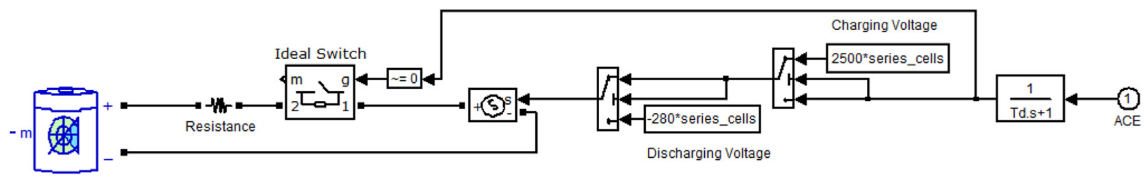

Fig. 6. Battery modeling using MATLAB Simulink for AGC.

term storage participation in AGC generally is, if ACE is negative due to net-load increase and frequency dips, then storage discharges short burst of power to offset it, and if ACE is positive due to net-load decrease causing frequency increase, then storage quickly absorbs power.

In this paper battery storage technology is used to represent this class of fast-responding short-term storage. Batteries store electrical energy in the form of chemical energy. Among the many available battery models such as Lithium-Ion, Lead-Acid, Nickel–Cadmium, Nickel–Metal-Hydride (Ni–MH), Sodium Sulfur (NaS), and flow batteries, in the simulations Ni–MH[1] battery model of Simulink is used with suitable parameters to realize a 1 MW 1200 V 1000 A (66.67 Ah, 0.08 MWh) battery with a response time of 100 ms. Fig. 5 shows the logic of integrating battery into AGC and its realization using Simulink is shown in Fig. 6. The battery internal voltage, a function of its SoC, is always positive and the current is bidirectional. At full-charge the battery voltage is at its maximum rated voltage of about 1200 V and decreases as the SoC decreases to a low of 1020 V. The battery is connected to the grid through ac/dc converter. The voltage across the converter (V_{conv}) is a function of the system ACE. The change in the voltage is proportional to the deviation in the system frequency and consequently the ACE, as given by (5) in the frequency domain.

$$\Delta V_{conv}(s) = \left(K_0 / 1 + sT_d\right) \mathrm{ACE} \tag{5}$$

As shown in Fig. 5, a positive voltage across the first convertor (i.e., positive ACE) triggers the convertor leg to apply 2500 V across the battery terminals, whereby the battery is charged. A negative voltage (negative ACE) across the first convertor triggers the convertor leg such that −280 V is applied across the battery terminals, thereby discharging the battery. When the deviation is 0, the battery terminal is open-circuited thereby not charging or discharging. As the current flows from or into the battery, the battery discharges or absorbs power, and its SoC changes. The converter voltage varies from −280 V to 2500 V, such that the maximum current is restricted to 1000 A (with net resistance across the battery being 1.48 Ω).

The parameter *series_cells* in Fig. 6 is used in the model (within and outside the battery) to increase the battery power rating by emulating the series connection of many cells that adds up all the voltage to make up a high-power battery bank with similar A-h rating.

3.3. Impact of wind penetration on AGC

The total wind generation in the system is split into buses 17, 21 and 22 respectively in the ratio 3:4:3. The data for load and wind generation at 1-min. resolution is taken from CAISO for two typical winter days. The net-load data at 1-s resolution is obtained by interpolating this 1-min data, and the net-load deviation at 1-s resolution for the simulation is computed as per (4).

As wind penetration increases, three kinds of impact on AGC model is captured within the simulations:

i) Increase in net-load deviations
ii) Higher allocation of regulation service by SCED
iii) Decrease in system inertia

Fig. 7 shows the net-load deviations for the two days (172,800 s) at different wind penetrations. It can be observed that the deviation increases as the wind penetration increases, with the peak deviation at 60% wind penetration about 5–6 times the peak deviation at 10% wind penetration.

The increase in net-load deviations with increasing wind penetration imposes higher ramping and regulation requirements on the generators in AGC. Fig. 8 shows the total hourly (3600 s) regulation allocations by the DA-SCED at various wind penetrations, since the estimation of hourly regulation requirements within the DA-SCED algorithm is made a function of net-load variability within every hour [18]. At each hour, the regulation requirements are allocated amongst coal (regulation offer = \$36), natural gas (\$27) and oil (\$62) units, with coal and gas units taking the bulk of the regulation services due to their offers.

As the wind generation increases, the system usually experiences reduction in inertia (H) mainly due to the displacement in conventional units [19]. In this study, this phenomenon is quantitatively captured using the hourly schedules from SCUC module. The system inertia for AGC simulation is computed as a function of the generators committed during every hour, as decided by the SCUC. Fig. 9 shows the impact of increasing wind penetration on system inertia every hour (in terms of percentage of the total

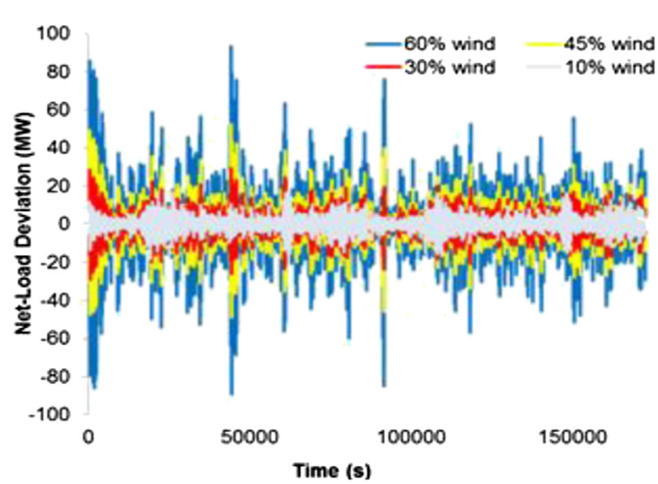

Fig. 7. Net-load deviations at various wind penetration at 1-s resolution.

[1] The paper is investigating the impact of short-term class of storage on frequency response, and is providing a methodology to quantify and monetize the associated benefits. It is not trying to answer which battery/device is best suited for this application.

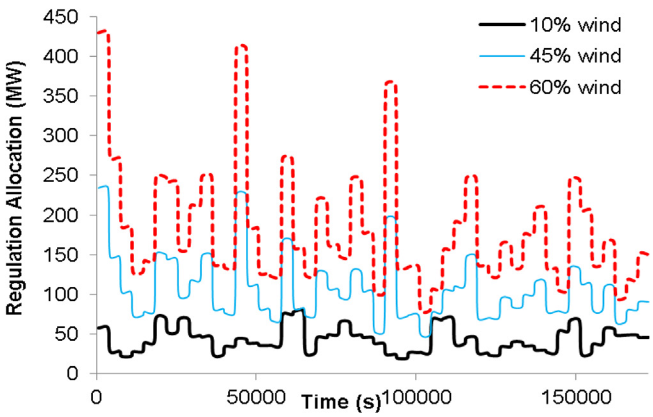

Fig. 8. Hourly regulation allocations at various wind penetrations.

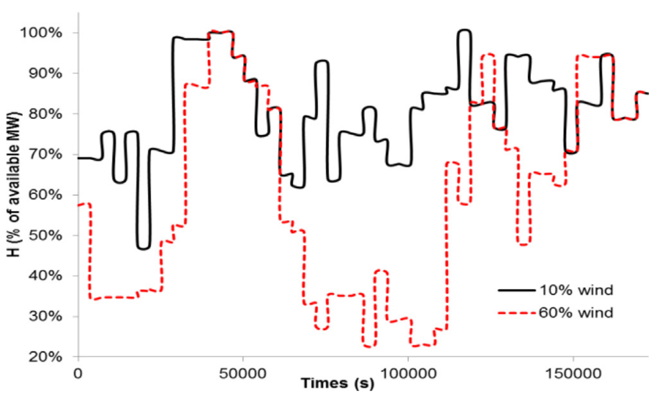

Fig. 9. Impact of increasing wind penetration on system inertia.

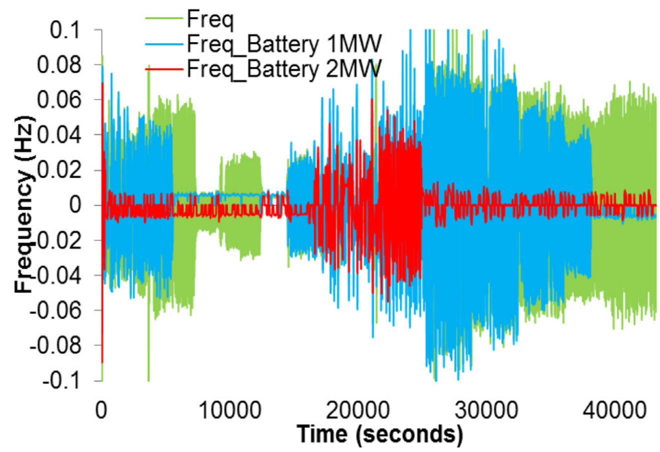

Fig. 10. Frequency response at 10% wind penetration.

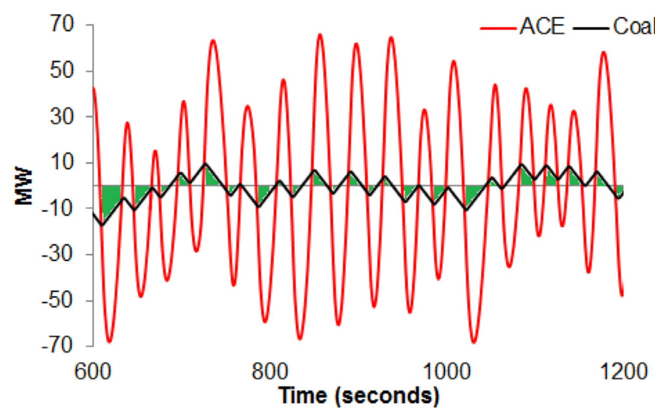

Fig. 11. ACE vs. generation – without storage.

system H (MW s^{-1})). This is accomplished by updating Tp in Fig. 2, which is a function of H (directly proportional).

There is decrease in the inertia during many hours due to displacement of conventional units by wind generation. The degree of conventional unit displacement also depends on many other factors such as forced outage of generators (captured within the SCUC using a random sampling process based on unit forced outage rates), load level, and wind spillage due to transmission flow limits.

4. Simulation results

Three cases were investigated. Case 1 is the normal case with the existing generators providing regulation through AGC according to the dispatch set points obtained from SCUC-SCED. Case 2 and case 3 are case 1 with the addition of 1 MW and 2 MW batteries respectively.

4.1. Frequency response assessment

Fig. 10 shows the 12-h frequency response at 10% wind penetration, for all the three cases respectively. It is seen that the frequency response is progressively better with increasing battery contribution in the system.

Figs. 11 and 12 show the ACE movement vs. generation movement over a period of 10 min for case 1 and case 3 respectively. According to the SCUC–SCED decisions, in this period only coal units are dispatched to supply regulation, and hence respond to the AGC signals.

The following can be observed from the two figures:

1. When battery contributes to frequency regulation in Fig. 12, the ACE is highly reduced due to its very fast movement, compared to coal alone trying to supply regulation as seen in Fig. 11. Just comparing the peak ACE, an improvement of about 7-times is observed.
2. The reduction in ACE and consequently in frequency deviation as observed in Fig. 10 is due to the fast response of batteries

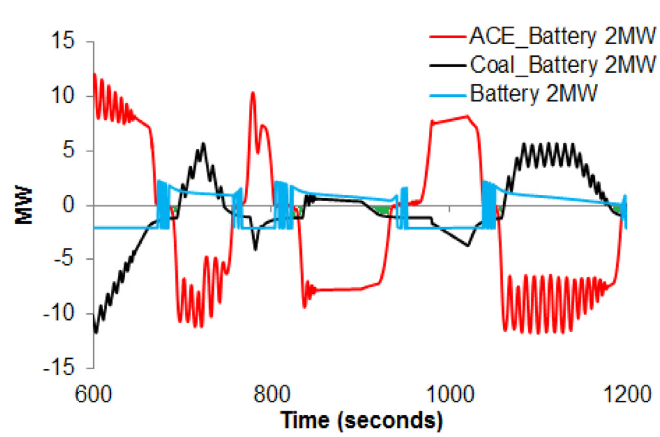

Fig. 12. ACE vs. generation – with storage.

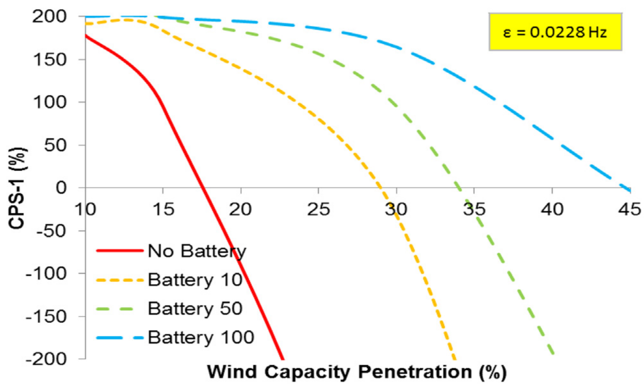

Fig. 13. CPS-1 at various wind penetration – $\epsilon = 0.0228$ Hz.

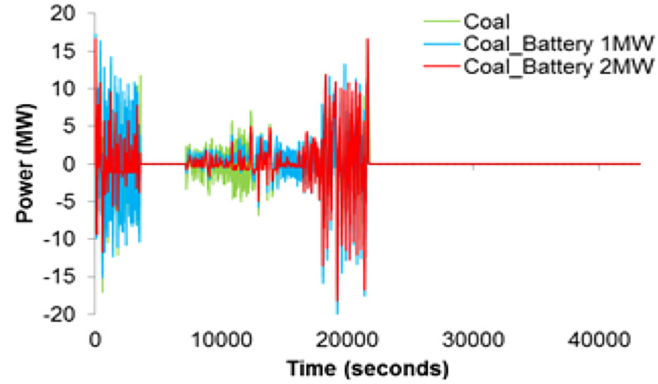

Fig. 15. Coal unit movement for various cases.

compared to conventional units. As seen in Fig. 11, many times coal unit due to its slow movement is unable to respond to the steep ramps of ACE caused by net-load fluctuations. Because of that even though coal unit move to offset the net-ACE, still it contributes to the total system ACE as seen by the shaded regions. The performance of conventional units will be much poorer with increasing wind penetration. On the other hand, as seen in Fig. 12, due to battery's very quick response, the ACE is offset instantaneously. Due to efficient frequency response, and highly reduced ACE movement, the coal movements are also less and do not contribute to system net ACE.

4.2. CPS1 measure

Fig. 13 shows CPS1 curves with $\epsilon = 0.0228$ Hz at various wind penetration levels. It is seen that without fast responding storage, for case 1 the CPS1 values decrease with increasing wind penetration. The available generating units are unable to offset the steep ramps of net-load deviation that occurs with increasing wind penetration. For the present case, beyond 15% wind penetration, the CPS1 values decrease less than 100%, and beyond 17.5% it is even worse.

The CPS may be improved by many ways, such as increasing fast acting regulation providers, aggregating control areas to reduce net-load variation, wind output control and inertia emulation, and increasing regulation requirement in SCUC/SCED algorithm. An ideal solution may be a combination of all these strategies, and fast responding devices may form a vital piece of that strategy. Fast responding regulation can be provided from combustion turbine, demand response and storage devices. In this study, the impacts of batteries are assessed. As seen in Fig. 13, with increasing penetration of fast responding storage, the CPS values are improving, thereby enabling higher penetrations of wind in the system without violating the NERC CPS criteria for frequency response. In this case study, an addition of 10 MW battery to the existing AGC fleet helps facilitate about 10–15% more wind integration without causing frequency issues. Fig. 14 shows the CPS1 curves with a slightly relaxed frequency bounds, with $\epsilon = 0.0342$ Hz. Consequently the CPS1 values are better in all the cases, again the addition of fast responding storage facilitating higher wind penetration.

4.3. Generation miles & regulation

Figs. 15 and 16 show the coal and natural gas units' movements for the first 12 h of the AGC simulation. The movements are termed as "mileage" [4], which denotes the net absolute MW movements in both the directions (up and down) made by a generator in response to AGC signal to offset ACE. The results are summarized in Table 2, where the bolded numbers within the brackets for cases 2 and 3 indicate the percentage decrease in the generation miles compared to the case 1. From Table 2 it is clear that with fast responding storage in the system, not only the total ACE-miles decreases, but also additionally the movements by conventional units, especially coal also decreases. Just an addition of a 2 MW battery to the AGC fleet in this case study reduces about 60% and 77% of contribution from coal and natural gas units respectively.

Table 3 shows the regulation in MWh expended from various units during the first 4 h under case 1 and case 3, where the bolded numbers within the brackets of the "Total" row indicate the percentage decrease in the amount of regulation deployed in the case 3

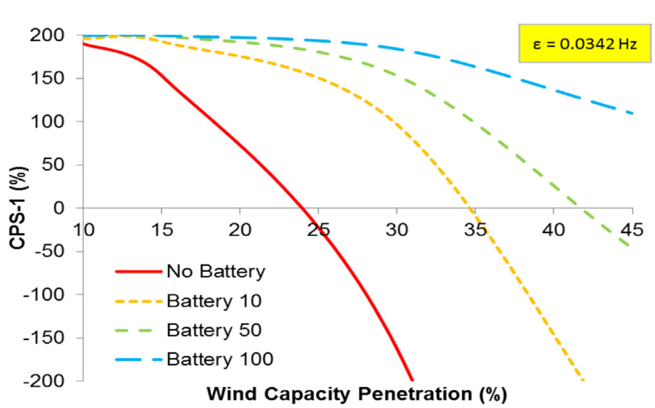

Fig. 14. CPS-1 at various wind penetration – $\epsilon = 0.0342$ Hz.

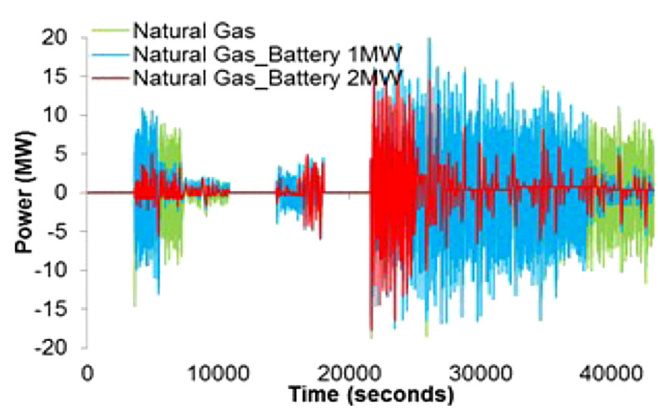

Fig. 16. Natural gas unit movement for various cases.

Table 2
Impact of battery on generation miles – wind pen 10%.

Case	ACE miles (MW)	Coal miles (MW)	Natural gas miles (MW)	Storage miles (MW)
1	1,533,481.99	4022.91	13,004.07	0
2	1,299,097.69 (−**15.28**)	3058.43 (−**23.97**)	10,738.32 (−**17.42**)	2677.51
3	35,1546.93 (−**77.08**)	1633.36 (−**59.40**)	2933.50 (−**77.44**)	18,089.44

compared to the case 1. With the inclusion of 2 MW battery that can instantaneously respond to ACE fluctuations, the total regulation supplied over the 4 h decreases in case 3 by about 24.3% compared to case 1. In case 3, the battery supplies about 37% of the total regulation required, while regulation from coal and natural gas units reduced by about 45% and 65% respectively. The reduction in coal and natural gas unit participation and hence the reduction in their cycling also has an impact on the overall system operating cost, CO_2, SO_2 and NO_x emissions, and also on the forced outage rates and life of these conventional units that are not designed to cycle. The results shown are at 10% wind penetration. At higher wind penetration, the benefits from battery for frequency response and also for improving the health of the conventional units are highly pronounced and economically very valuable.

Decrease in the regulation deployment also means a decrease in the regulation capacity allocation by regulation market. As discussed in Sections 2.3 and 3.2, the hourly regulation requirements specified in SCUC–SCED models are a function of net-load variability and additional allocations (δ_{CPS}) to improve CPS standards as shown in (6). ERCOT allocates additional regulation by monitoring the CPS scores.

$$\mathrm{Reg}(t) = fn(\Delta\mathrm{NL}(t)) \pm \delta_{\mathrm{CPS}}(t) \tag{6}$$

Since these short-term storage devices improve the CPS even with lesser deployment of regulation as observed in Table 3, this could lead to reduction in the total hourly regulation allocations and consequently the production cost. This is illustrated in Table 4 for a higher wind penetration of 30%. Case A and Case B are two 48-h generation dispatch scenarios, with Case B allocating 40% higher regulation over Case A and consequently resulting in increased production cost of about $10,000 over the 48 h. Table 4 also shows the 12-h regulation deployed by AGC based on the allocation decisions of SCED. We can observe that increased regulation allocation in Case B is useful in deploying more regulation (about 17.5%) to ensure increase in CPS1 measure, though still lesser than 0. On the other hand, including a 1 MW battery to the SCED of Case A enables maintaining a good CPS1 score even with a similar regulation deployment, thereby saving the requirement for additional 40% capacity allocation for regulation services by the SCED. This reduces regulation market MCPs and the system production cost. Therefore a systematic feedback of CPS scores to SCED from AGC integrated with short-term storage (can be envisioned in Fig. 1) is useful in dynamically allocating higher quality reserves and ensuring economic system operations.

4.4. Economic implications

From the discussions in previous sections, the economic implications of using short-term storage could be in terms of:

1. Reduction in regulation deployment
2. Reduction in conventional unit cycling

Table 5 shows the MCPs, the revenue that battery earns by supplying regulation and the savings due to decrease in regulation deployment in the first 4 h. The table also estimates the reduction in cycling related costs in these hours, as a consequence of reduction in coal and NG unit deployments. According to the cycling studies done by Aptech [20,21], the estimation of cycling costs related to load following (which include components such as heat-rate degradation, operation and maintenance costs, forced outage rates and upgrades) on an average for a coal and NG unit is about $3.34 per MWh and $1.92 per MWh respectively. According to Table 5, battery in this case promises a minimum of about $97.5 savings (Reg + Cyc savings) in the first 4 h by virtue of its performance, i.e., instantaneous response and frequent cycling. Aptech studies also quote higher values of these cycling costs, depending upon the specific characteristics of each unit and the ramp rates they are subjected to. These savings may further increase when reduction in emissions related to unsteady cycling operations are considered with a suitable emission tax.

NE-ISO proposes to pay for these short-term storages based on performance, i.e., the actual mileage a device does [4]. This is to properly value the fast responding storage that cycle very rapidly to provide regulation.

$$\text{Mileage } \$ = (\text{MW miles})(\text{C–S})(\text{MCP}) \tag{7}$$

where, the capacity–service ratio (C–S) is the ratio of the MW capacity to the MW-miles a conventional regulation provider may perform within an hour. In this paper, we propose the following economic incentive for mileage performance of storage as expressed in (8), which will be credited to the hourly storage revenue.

$$\text{Mileage } \$ = \frac{(\text{Storage MW miles})}{(\text{Total Gen. MW miles})}(\$ \text{ Saving}) \tag{8}$$

The 2 MW battery, with an average of about 1507.45 MW-miles per hour (from Table 2), contributes about 79.8% of the total generation miles. Therefore, the additional revenue associated with the mileage-service over the first 4 h will be about $77.8, i.e., 79.8% of the $97.5 estimated savings, thereby totaling the revenue in these hours to be $187.44. With the payment for its performance the 2 MW battery makes about $46.86 per hour, compared to about $26.91 per hour otherwise. This impacts the payback period of the battery investment positively, and hence encourages penetration of such storage devices in order to effectively interconnect variable generation onto the grid.

Table 3
Impact of battery on hourly regulation deployments (MWh) – wind pen 10%.

Hour	Coal	Natural gas	Total	Coal_Batt2 MW	Natural Gas_Batt2 MW	Battery 2 MW	Total
1	3.89	0	3.89	2.35	0	1.04	3.38
2	0.08	3.44	3.52	0.002	1.00	0.68	1.68
3	1.04	0.72	1.76	0.45	0.44	0.72	1.61
4	2.02	0	2.02	1.07	0	0.72	1.79
Total	7.03	4.161	11.19	3.872 (−**44.9%**)	1.45 (−**65.2%**)	3.15	8.47 (−**24.3%**)

Table 4
Regulation and generation miles for 12 h – wind pen 30%.

Case (48-h Prod. Cost M$)	Regulation (MW-h)	ACE miles (MW)	Coal miles (MW)	Natural gas miles (MW)	Storage miles (MW)	CPS-I
A (2.32)	96.09	1,121,483	14,474	81,934.11	0	−205.2
B (2.33)	112.95	1,312,925	21,643.15	90,821.47	0	−107.4
A + battery1 MW	97.73	55,3531.3	12,143.19	57,112.54	8307.18	32.56

Table 5
Economic implications of battery in AGC.

H	MCP ($)	Batt2 MW ($)	Reg. saving ($)	Coal Cyc ($)	NG Cyc ($)
1	36	37.44	18.36	5.14	0
2	27	18.36	49.68	0.26	4.68
3	36	25.92	5.4	1.97	0.54
4	36	25.92	8.28	3.17	0
Total		**107.64**	**81.72**	**10.55**	**5.22**

5. Conclusion

In this paper, the impact of short-term fast responding storage on frequency response of the system is assessed. AGC model of single area IEEE 24 bus RTS system is used, and battery storage is integrated. The impact of increasing wind penetrations in AGC study is incorporated in terms of increasing net-load variations and consequently the increased regulation requirements, and the decrease in the system inertia as a function of hourly SCUC decisions. The results indicate the ability of the battery storage to improve frequency response in the face of increasing wind penetration, as inferred from CPS1 scores. The results also indicated the ability of such fast responding storage to mitigate ACE instantaneously, thereby ensuring good frequency response with lesser regulation procurements. Consequently, it was observed that cycling of conventional generation were reduced, promising better unit health. It was also learnt that incentivizing short-term storage's performance based on the system benefits it brings improves its economics. From the study, it can be inferred that inclusion of such short term storage technologies will enable higher penetration of wind, while also maintaining good CPS scores with lesser procurement and economical allocation of regulation services.

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